

Progenitors of Type Ia Supernovae: Binary Stars with White Dwarf Companions

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ABSTRACT

Type Ia SNe (SNe Ia) are thought to come from carbon–oxygen white dwarfs that accrete mass from binary companions until they approach the Chandrasekhar limit, ignite carbon, and undergo complete thermonuclear disruption. A survey of the observed types of binaries that contain white dwarfs is presented. We propose that certain systems that seem most promising as SN Ia progenitors should be more intensively observed and modeled, to determine whether the white dwarfs in these systems will be able to reach the Chandrasekhar limit. In view of the number of promising single–degenerate systems and the dearth of promising double–degenerate systems, we suspect that single–degenerates produce most or perhaps all SNe Ia, while double–degenerates produce some or perhaps none.

Subject headings: Binary stars: evolution - white dwarfs - Type Ia Supernovae

1. INTRODUCTION

Type Ia supernovae (SNe Ia) used as distance indicators for cosmology have revealed that the cosmic expansion is accelerating owing to the existence of some kind of “dark energy”, and plans are being made to discover and carefully observe numerous high–redshift SNe Ia in order to probe the nature of the dark energy. Thus it is important to identify the stellar progenitors of SNe Ia. The exploding star is thought to be a carbon–oxygen (CO) white dwarf (WD) that accretes mass from a binary companion until it approaches the Chandrasekhar limit (CL) of $1.4 M_{\odot}$, ignites carbon under electron–degenerate conditions, undergoes a thermonuclear instability, and disrupts completely (Nomoto et al. 1984; Woosley & Weaver 1986; Leibundgut 2000, 2001; Hillebrandt & Niemeyer 2000). However, the nature of the mass–donating star is not yet known (Branch et al. 1995).

About 75 percent of the observed WDs have masses near $0.6 M_{\odot}$, about 10 percent have lower mass near $0.4 M_{\odot}$, and about 15 percent have higher mass above about $0.8 M_{\odot}$.

(Liebert et al. 2005a; Vennes 1999). The SN Ia progenitor WD therefore must be a member of a close binary in which it can accrete at least a few tenths of a solar mass in order to reach the CL.

Two main scenarios have been proposed, involving either the merger of two WDs (the double-degenerate, or DD, scenario; Iben and Tutukov 1984), or a single WD that accretes from a normal companion star (the single-degenerate, or SD, scenario; Whelan and Iben 1973). Some population synthesis studies favor the DD scenario (e.g., Yungelson & Livio 1998), and recent observational studies have identified many DD binaries (Napiwotzki et al. 2004). However, not one of the observed DD systems has both an orbital period short enough to merge in a Hubble time and a total mass that exceeds the CL. In addition, the merger of two CO WDs may lead to accretion-induced collapse to a neutron star rather than to a SN Ia (Timmes et al. 1994; Nomoto & Iben 1985; Mochovitch et al. 1997; but see Piersanti et al. 2003). Therefore, the SD scenario is generally favored today. The most recent theoretical models of accreting WDs in the SD scenario find that some of them can reach the CL (Langer et al. 2000; Yoon & Langer 2003; Han & Podsiadlowski 2004).

In addition to population synthesis studies and theoretical models of accreting WDs, a more observational approach can be helpful. In this paper we consider various types of observed binaries that contain a WD (the SD scenario), and consider which of them are good candidates for approaching the CL.

The observed companions of WDs in binaries include main-sequence stars (MS), red-giant (RGB) stars, asymptotic-giant-branch (AGB) stars, and post-AGB stars. About 20 stars in the Yale Bright Star Catalog are known to have WD companions. This is an underestimate of the true number, in view of the observational difficulty of detecting WD companions of bright stars of spectral type earlier than F. The WDs can be spatially resolved in classical nearby visual binaries such as Sirius and Procyon, but in unresolved systems the WD is difficult to detect by optical spectroscopy. The WD can be detected at shorter wavelengths, provided that it is hotter than the primary star.

2. WHITE DWARF + MAIN-SEQUENCE STAR BINARIES

Barstow et al. (2001) resolved several Sirius-like binaries with a Hubble Space Telescope (HST) UV imaging survey of stars known to have hot WD companions that are unresolved from the ground. Of the 17 systems observed, eight were resolved with the Wide Field Planetary Camera 2, using various UV filters. Some of the unresolved systems seem to be close binaries such as HR 8210 = IK Peg (A8V), which has a short orbital period of 21.7

days (Vennes et al. 1998). Barstow et al. found 56 Per (F4 V), whose WD companion has a mass of $0.9 M_{\odot}$ (Landsman et al. 1996), and 14 Aur (F4 V) to be quadruple and quintuple, respectively. Close binary systems with WDs and multiple companions are important for understanding the dynamical, accretion, and evolutionary processes of WDs in such systems.

The ROSAT WFC and EUVE sky surveys have produced samples of WDs with K IV-V, G IV-V, F IV-V, A III-V, and low-mass M V secondary stars. Many of these systems show orbital characteristics of post-common-envelope (post-CE) binaries (Hillwig et al. 2000). A few systems composed of a DA WD and secondary stars with spectral types B to K and luminosity classes from V to III were found in IUE low resolution UV spectra. For example, HR 8210 contains an A8 V star and a DA WD with a mass well in excess of $1.0 M_{\odot}$. Vennes et al. (1998) studied some of the hot WDs in the EUVE Survey. Parameters of selected binaries with WD and MS stars of spectral types B1.5 V to K V are given in Table 1.

Burleigh & Barstow (2000) found that the B9 V star 16 Dra has a WD companion. White-dwarf companions to B and A stars are important since they provide an observational lower limit on the maximum mass of a MS star that can become a WD. Since WDs in such systems are expected to be massive (0.8 to $1.0 M_{\odot}$) and the MS stars evolve rapidly, WDs in such close binaries may evolve to SNe Ia. Handler et al. (2002) found that the single-lined eccentric-orbit spectroscopic close binary HD 209295, which has a 3.1 day orbital period, consists of an A9 V primary and a $1.04 M_{\odot}$ WD. The system seems to be similar to HR 8210. Vennes (2000) found that HR 2875 is a close triple system with B3.5 V + B6 V + a WD in excess of $1.0 M_{\odot}$. The B3.5 V + B6 V stars have an orbital period of 15 days with orbital eccentricity of 0.68. The close binary WD in HR 2875 is detected in the EUVE spectrum (Burleigh & Barstow 1998); its T_{eff} is estimated to be $\sim 45,000$ K. The WDs in HR 2875-like systems are expected to be massive since the MS companions are B3 V to B5 V stars. The GALEX UV survey may reveal additional close binaries with late B and early A stars plus hot and massive WDs, which will be candidate progenitors of SNe Ia.

There are several hot WD + M-dwarf binaries (Green et al. 2000), but the total mass of most such systems is much less than the CL. In any case, since the evolution of M dwarfs is very slow most of them will not become cataclysmic variables or SNe Ia. Frequently, the WDs in the Sloan Digital Sky Survey (SDSS) are accompanied by an unresolved or barely resolved MS (nearly always M dwarf) companion with a composite spectrum. Raymond et al. (2003) studied 109 of these in more detail, with the main goal of finding close pairs that might be pre-cataclysmic variables. They found that the WDs in these systems are fairly hot, with T_{eff} from 8000 to 42,000 K. However in all these systems the companion is an M dwarf. With the release of the third SDSS data set, some 501 such pairs have been discovered in which the companions are all M dwarfs (Silvestri et al. 2005).

Table 1. SELECTED WHITE DWARF + MAIN SEQUENCE BINARIES

	V	Sp	WD (M_{\odot})	Period (days)
HR 8210 = IK Peg = EUVE J2126+193	6.07	A8 V	1.25	21.72
HR 2875 (triple system)	5.42	B3.5 V+B6 V	1.0	15.081
HD 209295	7.3	A9 V	1.04	3.106
16 Dra (triple)	5.51	B9 V	0.8	...
HD 33959C = EUVE J0515+326 (triple)	7.95	F4IV–V	0.7	...
EUVE J0702+129	10.0	K0 V	0.93	...
EUVE J0228-613 = HD 15638	8.8	F6 V	1.10	...
HD 223816 = EUVE J2353-703	8.8	G0 V	0.95	...
HD 217411 = EUVE J2300-070	9.8	G5 V	1.16	...
EUVE J0044+095 = BD +08 102	10.16	K2 V	0.9	...
EUVE J1925-565	10.6	G 5 V	0.76	...
EUVE J1024+263 = HD 90052	9.6	F0 V	0.93	...
EUVE J0357+286	11.7	K 2 V	...	...
EUVE J0356-366	12.45	G2 V	...	...
EUVE J1027+323	13.0	G5 V	...	...

From the analysis of the extensive SDSS data it may be possible to find composite spectra of hot WDs and late B, A and F stars.

Another category of binaries with WD + MS stars is that of dwarf carbon stars (Green et al. 2000). These dwarfs became carbon-rich as a result of mass transfer during the AGB phase of the present WD companions. Some of the dwarf carbon stars with very high carbon abundances are expected to have hot WD companions (Heber et al. 1993; Liebert et al. 1994). Further observational study of a large sample of dwarf carbon stars is needed.

2.1. V 471 TAURI-TYPE BINARIES WITH WHITE-DWARF COMPANIONS

V 471 Tauri is a remarkable system in the Hyades cluster. It is an eclipsing binary whose components are a hot DA WD of $0.84 M_{\odot}$ and a K2 MS star of $0.93 M_{\odot}$, with an orbital period of only 12.5 hours. The high effective temperature and high mass of the WD present an evolutionary paradox (O’Brien et al. 2001). The WD is the most massive one known in the Hyades, but also the hottest and youngest, in direct conflict with expectation.

O’Brien et al. (2001) conclude that the WD is descended from a blue straggler. They suggest that the progenitor system was a triple. Two of the components merged, leaving a blue straggler and the K2 V star. The blue straggler evolved to the AGB phase and common envelope interaction with the K2 V star, which spiraled in to its present separation and ejected the envelope. The present K2 V component is found to be 18 percent oversized for its mass relative to normal Hyades K2 V stars of same mass. The evolution of the orbital period and the spiraling in of the K2 V star need to be explored to see if V 471 Tau-type systems can result in SNe Ia. Parameters of selected V 471 Tau-type binaries are given in Table 2.

Table 2. V 471 TAU-TYPE CLOSE BINARIES

	Period (days)	WD (M_{\odot})	T_{eff}	K V (M_{\odot})
V 471 Tau	0.5212	0.84	34,500 K	0.93
HS 1136+6646	1	...	100,000 K	...
BE UMa	2.291	0.7	105,000 K	...
EC 13471 - 1258	0.151	0.77	14,085 K	0.58

Common-envelope evolution is not well understood. However several types of binaries, such as cataclysmic variables, SN Ia progenitors, X-ray binaries, etc., seem to go through the CE phase. Post-CE binaries provide important observational constraints on theoretical models. Only about 25 post-CE binaries have measured orbital periods and far fewer have accurate component masses (Hillwig et al. 2000). The post-CE binaries BE UMa (sdO/DAO + K5 V; 2.29 day orbital period) and HS 1136+6646 (DAO + K7 V; 0.836 day orbital period) appear to be similar to V 471 Tau, except that BE UMa and HS 1136+6646 have very hot (105,000 K and 70,000 K) WDs. In all three systems the K V star is out of thermal equilibrium, resulting in radii larger than normal. The total mass of the components in BE UMa probably is close to the CL, as in V 471 Tau. Hillwig et al. (2000) listed several additional post-CE systems with very hot WD companions, but most of these have longer orbital periods and their total masses seem to be much less than the CL.

Schreiber & Gansicke (2003) analysed 30 well-observed post-CE binaries. In their sample only V 471 Tau has a total mass above the CL, although that of EC 13471-1258 (orbital period 0.151 days; WD mass of $0.77 M_{\odot}$; and mass of the MS component $0.58 M_{\odot}$) is very close to it. Schreiber & Gansicke calculated the orbital evolution of the systems and concluded that they will evolve into semi-detached configurations and begin mass transfer. They predict that the orbital period of V 471 Tau will decrease from its present 0.521 days to 0.167 days. Therefore V 471 Tau type systems can be considered as candidate progenitors of SNe Ia.

The GALEX UV survey may reveal a larger sample of binaries with hot, massive WDs and MS (and RGB, AGB, and post-AGB) companions. From a study of these systems we may be able to find some with orbital periods and accretion rates that are appropriate for evolution into SNe Ia.

3. BINARY ORIGIN OF MASSIVE WHITE DWARFS

Vennes (1999) and Marsh et al. (1997a,b) studied the properties of hot WDs in the EUVE and ROSAT surveys and found several massive WDs. Vennes (1999) listed 15 WDs more massive than $1 M_{\odot}$, and found in these a high incidence of magnetic WDs. He suggested that the magnetism may be due to magnetism of the MS progenitors and/or to post-AGB evolution affected by magnetic fields. He also suggested that the massive WDs may be products of close binary evolution.

Liebert et al. (2005a) studied 348 DA WDs in the Palomar Green (PG) survey and found eight high-mass WDs in their sample, whereas less than one was expected on the basis of the

standard WD mass distribution. The average mass of the eight high-mass WDs is $0.93 M_{\odot}$, including PG 1658+441 ($1.31 M_{\odot}$; Schmidt et al. 1992). In view of the apparent excess of high-mass WDs, several authors have suggested that a substantial fraction of the 0.8 to $1.35 M_{\odot}$ WDs may result from close binary evolution, i.e., mergers of helium + helium WDs, helium WD + CO WD, and CO + CO WDs.

If some of these massive WDs have close companions, accretion processes or mergers might produce SNe Ia, in which case some of the SN Ia progenitors are initially very close triple systems (in addition to the triple systems suggested for the origin of V 471 Tau type binaries discussed above).

From Sloan Digital Sky Survey data Kleinman et al. (2004) found 2500 new hot WDs, including 20 of high mass. Also several magnetic WDs have been found (Gansicke et al. 2002; Schmidt et al. 2003). A total of 169 magnetic WDs are now known, most having fields higher than 2 MG. Magnetic WDs with fields higher than 1 MG constitute about 10 percent of all WDs and have a mean mass of $0.93 M_{\odot}$ compared to $0.56 M_{\odot}$ for all WDs. Liebert et al. (2005b) noticed a curious, unexpected property of the total lists of magnetic WDs and of WD + MS binaries: there appears to be virtually zero overlap between the two samples. No confirmed magnetic WD has been found in a system with a MS star. This contrasts with the situation for interacting binaries, in which an estimated 25 percent of the accreting systems have a magnetic WD. It is possible that some of the magnetic WDs may have very close, unresolved MS companions of spectral type earlier than M, as opposed to the non-magnetic WDs in the SDSS data in which the companion is nearly always an M dwarf. It may be a selection effect in view of the large mass and small radius of magnetic WDs (Liebert et al. 2005a,b). The magnetic WDs have a higher than average mass because on average they have more massive progenitors, rather than because the initial-final mass relation (IFMR) is affected by the magnetic field of the progenitors (Wickramasinghe & Ferrario 2005). The magnetic WD progenitors may be stars with initial mass more than $4.5 M_{\odot}$ that had magnetic fields during the MS phase or generated magnetic fields during post-MS phases (Wickramasinghe & Ferrario 2005). Since a significant fraction of MS stars more massive than $4.5 M_{\odot}$ are close binaries, it is expected that a fraction of the magnetic WDs may contain unresolved companions. Radial velocity monitoring and multiwavelength observations of magnetic WDs are needed to search for companion stars and to understand the evolution of such systems into SNe Ia.

The IFMR is constrained by observations of WDs in clusters (Weidemann 2000). There is not much observational information on the IFMR at the high mass end. The current best estimate for the maximum initial mass is $6.5 M_{\odot}$, producing a WD of about $1 M_{\odot}$. Williams et al. (2004) and Kalirai et al. (2005) constrain the upper mass limit of WD progenitors to

be $5.8 M_{\odot}$ for a cluster age of 150 Myr. There seem to be no magnetic WDs in young open clusters, so the effect of magnetic field on the IFMR is unknown.

4. F, G, AND K GIANTS WITH WHITE-DWARF COMPANIONS

In addition to MS stars with WD companions, there are F, G, and K giants with WDs. The Ba II G III and K III stars and the CH stars are all have WD companions (McClure 1984; McClure & Woodsworth 1990; Böhm–Vitense et al. 2000), and carbon, barium, strontium, and other s–process heavy elements are overabundant due to mass accretion from the former AGB companion (now the WD). If Ba II and CH stars are assumed to have masses of $1.5 M_{\odot}$ and $0.8 M_{\odot}$, respectively, then the mass functions derived from the spectroscopic orbits are such that the WD companions are around $0.6 M_{\odot}$ similar to that of a typical field WD. The WD companions of a few Ba II stars with short orbital periods may accrete enough mass to reach the CL during the Roche lobe overflow or during the AGB phase of the present G–K giants, as the total mass of the some Ba II binaries is expected to be more than $2 M_{\odot}$. The total masses of CH–star systems appear to be too low to produce SNe Ia.

Based on UV spectra of Ba II stars obtained with the HST, Böhm–Vitense et al. (2000) concluded that it is indeed highly probable that all Ba II and mild Ba II stars have WD companions, which in most cases are rather cool and therefore old. Most Ba II stars must have come from B or possibly early A MS stars. The MS F stars, with masses around $1.5 M_{\odot}$, do not produce many Ba II stars. The incidence of Ba II stars among giants is about one percent (Böhm–Vitense et al. 2000). Therefore it is expected that nearly one percent of MS early A and late B have WD companions, which are expected to be hot and young. Systematic radial–velocity and far–UV surveys are needed to search for such systems, which may be candidate SN Ia progenitors.

Subgiant CH stars (Bond 1974; Luck & Bond 1991; McClure 1997), dwarf Ba II stars (North et al. 2000), dwarf carbon stars, and F V stars with strong Sr II 4077 Å lines (North et al. 2000) also have WD companions and overabundances of carbon and s–process elements. It is likely that subgiant CH stars and dwarf Ba II stars are precursors to giant Ba II stars. Most of the known Ba II, CH, and subgiant CH stars, etc., are very long period binaries (McClure & Woodsworth 1990; McClure 1997) and the masses of the primaries are low, therefore most of these systems are not candidate SN Ia progenitors.

The Tc–poor S stars are evolved Ba II stars (Iben & Renzini 1983) with orbital elements similar to Ba II stars. The no–Tc S stars consist of mass–losing S giants (on the AGB) with WD companions (Jorissen 1999; Van Eck & Jorissen 2002). Orbital periods are found to be

similar to those of symbiotic systems. Some no-Tc S-star binaries have been found to show symbiotic activity (Van Eck & Jorissen 2002). Symbiotic binary S stars are more evolved than non-symbiotic binary S stars, and mass-loss from the S star and accretion onto the WD produces the symbiotic activity.

Further studies, especially far UV, of Ba II G–K giants, CH giants, subgiant CH stars, F V stars with strong Sr II 4077 Å lines, dwarf carbon stars, no-Tc S stars, and yellow symbiotics may reveal some short-period systems with massive WD companions. We do not have orbital parameters for many of these systems.

There are six known D'-type (dusty) symbiotic binaries, also called yellow symbiotics. These are binaries with F–G giants and WD companions. Circumstellar dust and emission lines are present, and the giants rotate rapidly. Carbon and s-process elements are overabundant (Pereira et al. 2005). Since the F–G giants in these stars are more massive than the K giants in Ba II stars and the orbital periods (a few hundred days) are shorter, these systems may also be candidate SN Ia progenitors. Evolutionary models of these systems need to be computed to understand if they can produce SNe Ia by accretion or mass transfer during Roche-lobe overflow, or during the AGB mass-loss phase of F–G stars.

5. HYDROGEN-POOR CLOSE BINARIES

Only four hydrogen-poor close binaries (Upsilon Sgr; HD 30353 = KS Per; LSS 4300; and CPD -58 2721 = LSS 1922; see Table 3) are known, which indicates that these are very rare systems. In these systems the primary is a very hydrogen-poor A supergiant and the secondary is a hot evolved star or a MS star. These four systems are single-lined spectroscopic binaries. The IUE UV spectra of Upsilon Sgr and HD 30353 show P-Cygni stellar wind profiles of lines of N V, C IV, Si IV, etc., indicating mass loss. The presence of N V and C IV lines and the UV continuum indicates that the secondary components are hot stars.

Table 3. HYDROGEN-POOR CLOSE BINARIES

	Period (days)	F(m)	T_{eff}	$M1_{\odot}$	$M2_{\odot}$
Upsilon Sgr	137.95	1.44	11,800 K	1.0	4
HD 30353	362.8	3.6	12,500 K	1.0	5
LSS 4300	52.09	0.79	12,000 K	1.0	3–4
CPD -58 2721	43	1	12,000 K	1.0	2–3

However in the optical spectra the secondary components are not detected. The secondary components may be obscured, because the IRAS data indicates the presence of warm and cold circumstellar dust. The presence of warm-dust envelopes indicates recent mass-transfer and mass-loss processes. The masses of the primary and secondary components are not well determined. High resolution, high signal-to-noise ratio UV spectra may reveal the spectral lines of the hot secondary components and allow the determination of radial-velocity curves and masses. Accurate determination of the masses is needed to compute evolutionary models of these systems. The mass-function $[F(m)]$ values derived from the single-lined spectroscopic orbits suggest that the hydrogen-poor primaries may have CO core masses of about 1.0 to 1.3 M_{\odot} with thin extended outer envelopes. They may be in the post-AGB stage. In Table 3 the primary masses are all taken to be 1.0 M_{\odot} . Mass transfer from the secondary components during the Roche-lobe overflow and common-envelope phase may result in SNe Ia (Morrison 1988; Uomoto 1986).

6. BINARY BLUE METAL-POOR STARS AND BLUE STRAGGLERS

6.1. Binary Blue Metal-Poor Stars

Among the blue metal-poor stars (spectral types A to F) several binaries have been found. These have overabundances of carbon, lead, and other s-process elements (Preston & Sneden 2000, 2005; Sneden, Preston, & Cowan 2003). The binary blue metal-poor star CS 29497-030 has an extreme enhancement of lead, $[Pb/Fe] = +3.7$, the highest seen in any star so far. The overabundances seem to have been acquired during the AGB and post-AGB evolution of the companion stars, which are now WDs (Preston & Sneden 2005). Model evolutionary calculations are needed to see whether future Roche-lobe overflow or AGB phases of the blue metal-poor stars may produce SNe Ia. Of 62 blue metal-poor stars investigated by Preston & Sneden (2000), two thirds are in single-lined spectroscopic binaries with orbital periods of two to 4000 days. Studies of large samples of blue metal-poor stars may reveal short-period systems with total mass exceeding the CL.

6.2. Binary Blue Stragglers

Blue stragglers are present in globular clusters, in old and young open clusters, and in the field. Their evolution cannot be explained by canonical stellar evolutionary models. The explanations for their formation involve mass transfer in and/or mergers of binaries, or stellar collisions. All these mechanisms may be at work in globular clusters. Recent studies

of blue stragglers in globular clusters and in the field indicate that most of the blue stragglers are binaries and a large fraction of them may contain WD companions. Carney et al. (2005) studied the radial-velocity variations of several metal-poor field blue stragglers, all known to be deficient in lithium. They found all of them to be single-lined spectroscopic binaries with periods ranging from 302 to 840 days, similar to findings of Preston & Sneden (2000) for other blue-straggler candidates. Preston & Sneden (2000) and Sneden, Preston, & Cowan (2003) concluded that field blue stragglers are created almost solely by mass transfer. Carney et al. (2005) argued that the secondaries in all these systems are WDs. They found a steeper mass function for blue straggler binaries than for lower-mass single-lined spectroscopic binaries, indicating a narrower range in secondary masses. They also found that the orbital elements of all metal-poor binary blue stragglers are consistent with stable mass transfer, which indicates that stable mass transfer and accretion onto the WD may take place during the Roche-lobe overflow or AGB phases of the blue stragglers. Some of these systems with short orbital period and total mass exceeding the CL may produce SNe Ia.

6.3. Carbon- and s-Process-Rich Very Metal-Poor Binaries

From an analysis of observed radial-velocity variations of very metal-poor and carbon-rich stars with overabundances of s-process elements Lucatello et al. (2005) found that the binary fraction among these stars is higher than that found in the field, suggesting in fact all of these objects are binaries, with WD components. The overabundance of carbon and s-process elements is the result of accretion and mass transfer during the AGB stage of the present WD companions. The orbital periods of some of these systems are found to be short. Long-term radial-velocity monitoring of a large sample of these stars can lead to the accurate determination of orbital elements and masses of the components. Some systems with short orbital periods and massive WDs and total mass exceeding the CL are expected. The HK survey (Beers et al. 1992; Beers 1999) and the Hamburg-ESO survey (Christlieb et al. 2001a,b; Christlieb 2003) of large samples of very metal-poor stars have shown that up to 25 percent of stars with metallicities lower than $[\text{Fe}/\text{H}] = -2.5$ are carbon-enhanced, ($[\text{C}/\text{Fe}] \gg 1.0$). Until recently the origin of these stars and the origin of the overabundances of carbon and s-process elements remained unclear (Norris et al. 1997; Aoki et al. 2001, 2002a,b,c). Such metal-poor stars in binaries with short orbital periods and massive WD companions may produce SNe Ia. Several of these stars have T_{eff} in the range of 6000 K to 7000 K and surface gravities ($\log g$) in the range of 3 to 4. Further radial-velocity studies and UV spectra may enable us to estimate the masses of the WD companions. If the WD mass is $0.6 M_{\odot}$, then some of these systems seem to have total mass exceeding the CL. The above described three groups of binaries with WD companions (binary blue metal-poor stars,

blue stragglers, and carbon and s-process-rich metal-poor binaries) seem to be related.

7. AGB STARS WITH WHITE-DWARF COMPANIONS

Mass transfer from carbon-rich AGB stars with WD components can occur through stellar wind or Roche-lobe overflow (Iben & Tutukov 1985). Roche-lobe overflow seems unavoidable in systems with circular orbits and periods shorter than a few hundred days. Roche-lobe overflow from an AGB star with a deep convective envelope leads to a CE phase and a short orbital period (Iben 1995). Detailed evolutionary model calculations are needed to understand if AGB binaries with WD components can result in SNe Ia. An AGB star in the progenitor system of the strongly circumstellar-interacting Type Ia SN 2002ic was suggested by Hamuy et al. (2003).

Carbon symbiotics (carbon stars with WDs) are present in the LMC and SMC. Further study of these systems is needed.

8. POST-AGB BINARIES

A few post-AGB binaries are known. Very metal-poor post-AGB A and F supergiants (Table 4) are single-lined spectroscopic binaries with orbital periods of several hundred days (Van Winckel et al. 1995). The post-AGB stars in these systems have WD-like CO cores, and thin extended envelopes of 0.01 or 0.02 M_{\odot} , and circumstellar dust disks (Cohen et al. 2004; Van Winckel et al. 2000). There are a few more post-AGB binaries with dusty circumstellar disks. In all these systems the secondaries seem to be obscured by dusty disks. For the progenitor of the SN 2002ic, Kotak et al. (2004) favor a single-degenerate system in which the donor is a post-AGB star.

The bipolar protoplanetary nebula M1-92 contains a binary consisting of a WD and a F supergiant (Arrieta et al. 2005); an accretion disk around the WD is suggested. Far IR observations indicate the presence of a large dusty torus. IRAS 08544-4431 also is a post-AGB star in a binary with a dusty disk (Maas et al. 2003), HD 172481 is a post-AGB binary with a red AGB star (Reyniers & Van Winckel 2001), and Hen 3-1312 is a post-AGB binary (Pereira 2004).

Gordon et al. (1998) found that the eclipsing double-lined spectroscopic binary HD 197770 is an evolved system with at least one of the components in the post-AGB stage. The orbital period is 99.69 days and the masses of the components are 2.9 and 1.9 M_{\odot} . The spectral types of both stars are B1 V-III or near B2 III, so both components are undermassive by

about a factor of five, and thus are evolved stars. Additional evidence of the evolved nature of HD 197770 is found in the 25, 60, 100 micron IRAS images, which show two associated dust shells. Chemical composition analysis of both components from the analysis of high resolution spectra is needed. The C, N, and O abundances may enable us to further understand the evolutionary stage (and mass-transfer and mass-loss) of both components. Close-binary evolutionary model calculations of this system may enable us to understand if it will produce a SN Ia.

9. BINARY CENTRAL STARS OF PLANETARY NEBULAE

Sixteen planetary nebulae (PNe) are known to contain close-binary nuclei (Bond 2000) with orbital periods from 0.1 to 3 days (Table 5). The central stars (CSPNe) have CO core masses of about $0.6 M_{\odot}$. It is estimated that 10 percent of PN nuclei may be very close binaries (Bond & Livio 1990). The short orbital periods indicate that the PNe must have been ejected during CE phases.

Three PNe with binary nuclei (Abell 35, LoTr 1 and LoTr 5) have optical spectra dominated by late G–K stars, but whose UV spectra indicate the presence of extremely hot (100,000 K) WD companions (Bond & Livio 1990). The G–K stars are rapidly rotating and have active chromospheres. The hot WDs in these three systems have masses more than $0.6 M_{\odot}$. Mass loss and mass transfer from the G–K components during the Roche-lobe overflow or AGB phases may result in SNe Ia. Evolutionary model calculations need to be carried out.

Bond et al. (2002) found that PN SuWt 2 is a triple system consisting of two A stars with 4.9 day orbital period and a hot CSPN. The PN appears as an elliptical ring with much

Table 4. POST-AGB BINARIES

	Period (days)	e	f(m)
HR 4049	429	0.31	0.143
HD 44179	318	0.38	0.049
HD 52961	1305	0.3	0.46
HD 46703	600	0.34	0.28
BD +39 4926	775	...	...
HD 213985	259	...	0.97

Table 5. CLOSE BINARY CENTRAL STARS OF PLANETARY NEBULAE

PN	central star	Period (days)
Abell 41	MT Ser	0.113
DS 1	KV Vel	0.357
Hf 2-2	(MACHO var)	0.399
Abell 63	UU Sge	0.465
Abell 46	V 477 Lyr	0.472
HFG 1	V 664 Cas	0.582
K 1-2	VW Pyx	0.676
Abell 65	...	1.0
HaTr 4	...	1.74
Tweedy 1	BE UMa	2.29
SuWt 2	...	2.45
Abell 35	BD -22 3467	...
LoTr 1	...	...
LoTr 5	HD 112313	...

fainter bipolar lobes. Bond et al. (2002) suggest that SuWt 2 and V 471 Tau (§ 2.1) are exotic descendants of triple systems. The masses of the A stars in SuWt 2 are both near $2 M_{\odot}$, so the initial mass of the CSPN was more than $2 M_{\odot}$.

G135.6+01.0 = WeBo 1 contains a close binary consisting of a late-type giant and a hot CSPN (Bond et al. 2003). The giant is overabundant in carbon and s-process elements which indicates that mass transfer and/or accretion has taken place during the AGB stage of the CSPN. Further study of WeBo 1 and SuWt 2 including the measurement of orbital periods and masses of the components may enable us to understand if such close-binary CSPNe can produce SNe Ia.

Wolf-Rayet (WC) CSPNe are hydrogen deficient and overabundant in helium and carbon. About 10 to 15 percent of CSPNe are of type WC. From ISO observations, a dual dust chemistry (oxygen- and carbon-rich) is almost exclusively associated with WC CSPNe. Oxygen-rich dust resides in a disk, while the carbon-rich dust is more widely distributed. HST STIS spectroscopy of the WC CSPN CPD -56 8032 indicates the presence of a dust disk or torus. All the WC PNe are IRAS sources. From a radial-velocity survey of 18 WC CSPNe De Marco et al.(2004) found 8 WC stars showing radial-velocity variations, indi-

cating binarity. De Marco et al. concluded that all WC CSPNe are binaries. Evolutionary model calculations are needed to understand if binary WC CSPNe can produce SNe Ia.

G135.9+55.9, a PN in the Galactic halo, contains a close-binary nucleus with short orbital period (Tovmassian et al. 2004). From radial-velocity data the mass of the WD is about $0.9 M_{\odot}$ and the mass of the CSPN is about $0.55 M_{\odot}$; the total mass exceeds the CL and this system may produce a SN Ia.

10. SYMBIOTIC STARS

Symbiotic stars are interacting binaries consisting of a red giant and a WD. The D-type symbiotics have warm circumstellar dust and the cool components of many of these are Mira variables. Some of these have bipolar nebulae. There are several symbiotics in which the donor stars are of types G–K. The total mass of such systems exceeds the CL. The spectra reveal accretion and mass transfer from the G–K companion to the WD. We need to derive accurate orbital periods, masses, and accretion and mass transfer rates. Since the G–K–M stars in the symbiotics are AGB stars the orbital periods are longer. In several of the D-type symbiotics the pulsating Mira variables show evidence for mass loss and for the presence of cool and warm circumstellar dust. The WDs in D-type symbiotics with periods in the range of 200 to 600 days may have relatively high accretion rates, as the mass-loss rates from the companion Miras are on the order of $10^{-7} M_{\odot} \text{ y}^{-1}$.

Mira is an interacting binary consisting of a Mira-variable AGB star (Mira A) and an accreting WD (Mira B). Mira A is losing mass at a high rate ($\sim 10^{-7} M_{\odot} \text{ y}^{-1}$). The system has been studied using HST and CHANDRA (Karovska et al. 2005). The symbiotic binaries CH Cyg and R Aqr are similar to Mira. Evolutionary model calculations of these systems are needed to understand if they will produce SNe Ia. The large X-ray outburst in Mira A detected by CHANDRA may have been caused by a magnetic flare followed by a large mass ejection (Karovska et al. 2005). Such large-scale mass ejections from Mira A may result in an increased accretion rate onto the WD. If they occur often, such events in Mira and in other symbiotics may enable the WDs to reach the CL. Munari & Renzini (1992) argue that only 4 percent of the symbiotics in the Galaxy need to evolve to SNe Ia in order to account for the observed SN Ia rate. However Kenyon et al. (1993) countered that symbiotics probably cannot produce SNe Ia at a significant rate (see also Yungelson et al. 1995).

Some symbiotics (R Aqr, AG Dra, RR Tel, CD-43 14304, and J0048 and Ln358 in the SMC) are supersoft X-ray sources (SSXSs; Greiner 1996). There seems to be two groups of symbiotic SSXSs: symbiotic novae (e.g., RR Tel, J0048) and quiescent symbiotics (AG Dra

and most others). Symbiotic novae have strong soft X-ray emission during their optical outburst. On the contrary, AG Dra displays soft X-ray emission in its quiescent state (Greiner et al. 1997). It is not clear if the WDs in some of these systems can gain enough mass to reach the CL. In the LMC and SMC the WDs in some of the symbiotics have high luminosities ($3000 L_{\odot}$) and effective temperatures (130,000 K) which indicates that they are at the upper end of the luminosity function (Mürset et al. 1996). There are about six symbiotics in the SMC with WD temperatures in the range 1.3 to 2×10^5 K, WD masses of about $0.7 M_{\odot}$ (Iben 1982), and red-giant masses of about $3 M_{\odot}$. Kahabka (2004) studied the six-year supersoft X-ray light curve of the symbiotic nova SMC 3 = RXJ0048.4-7332. He found that the $0.8 M_{\odot}$ WD is undergoing steady nuclear burning with an accretion rate close to $10^{-7} M_{\odot} \text{ y}^{-1}$, and he suggested that it may become a sub-CL SN Ia (although it is doubtful that sub-CL WDs can explode). Monitoring of the following symbiotic binaries may enable us to understand if some of them can produce SNe Ia: Mira, CH Cyg, V741 Per, Wray 157, AS201, BD-21 3873, He2-467, S190, and the symbiotic SSXs RR Tel, AG Dra, R Aqr, CD -43 14304, and the SMC symbiotic SSXs J0048, Ln358, and SMC 3 = RXJ0048.4-7332.

11. DWARF NOVAE

Cataclysmic variables (CVs) with accreting WDs consist of several types, such as classical novae, recurrent novae, nova-like variables, dwarf novae, helium CVs, and magnetic CVs. The total mass in most CV systems is much lower than the CL. There are a few dwarf novae in which the WD is about $1 M_{\odot}$: GK Per, SS Aur, HL CMa, U Gem, Z Cam, SY Cnc, OY Car, Z Cam, TW Vir, AM Her, SS Cyg, RU Peg, GD 552, and IP Peg. The secondaries are K and M stars. A few of these systems with early K type secondaries may have total mass close to the CL. Accurate determination of masses of the components in these systems is needed. King et al. (2003) considered the CVs with massive WDs as candidate SN Ia progenitors. From multiwavelength studies of the properties of the accreting WDs in dwarf novae during quiescence we may be able to estimate the WD masses. RU Peg has a massive WD ($1.29 M_{\odot}$) and the secondary is a K2 V star. The orbital period is 8.99 hours (Stover 1981; Wade 1982; Shafter 1983). The near-Chandrasekhar mass of the WD has been corroborated by the sodium 8190 Å radial-velocity study of RU Peg by Friend et al. (1990), who obtained a WD mass of $1.24 M_{\odot}$ and also found very good agreement with the solution, including the range of plausible inclinations, of Stover (1981). The total mass of the system exceeds the CL. RU Peg undergoes dwarf nova outbursts every 75 to 85 days, with outburst amplitudes of three magnitudes and durations of three days (Ritter & Kolb 1998). Between outbursts RU Peg has a steeply rising far-UV continuum. From a detailed analysis of IUE spectra of RU Peg during quiescence Sion & Urban (2002) found the WD T_{eff} to be 50,000 K.

They conclude that RU Peg contains the hottest WD yet found in a dwarf nova. The WD of RU Peg is 15,000 K, hotter than the hottest WDs in dwarf novae (U Gem and RX And) above the period gap. RU Peg’s WD is in the temperature regime occupied by the WDs in the nova-like variables UX UMa and VY Scl. The accretion disk in RU Peg may be among the largest of any dwarf nova (Sion & Urban 2002). The accreting WD in RU Peg with $T_{\text{eff}} = 50,000$ K should have an envelope thermal structure that could support thermonuclear burning. Further studies of RU Peg and similar systems with massive WDs are needed to understand if they evolve to SNe Ia. There may be short and long term variations in the accretion rates, i.e., at times it may be only 1 to $2 \times 10^{-9} M_{\odot} \text{ y}^{-1}$ and at other times as high as $10^{-7} M_{\odot} \text{ y}^{-1}$. Further study of RU Peg-type systems with massive WDs may enable us to understand if some of them can become SNe Ia.

From SDSS data Szkody et al. (2006) discovered a large number of new CVs, including many interesting systems such as eclipsing, pulsating, and magnetic CVs. This database is a good resource for population and evolution studies of CVs, pre-CVs, and WD companions. Detailed studies of these systems are needed.

12. RECURRENT NOVAE

Recurrent novae, in which a WD accretes from a red giant, have been considered as candidate SN Ia progenitors (Starrfield, Sparks & Truran 1985; Hachisu & Kato 2001). From detailed modeling of the decline of the outburst light curves of T CrB, RS Oph, V745 Sco, and V3890 Sgr, Hachisu & Kato (2001) suggest that the WDs are approaching the CL (Table 6) and will become SNe Ia. Wood–Vasey & Sokolowski (2006) proposed that a shell ejected by a recurrent nova created the evacuated region surrounding SN 2002ic. They suggest that recurrent novae are SN Ia progenitors, with the periodic shell ejections creating structure in the circumstellar region.

RS Oph is one of the well-observed recurrent novae and is suggested to be a SN Ia progenitor system (Hachisu & Kato 2001). It underwent its sixth recorded outburst on 2006 February 12 (Narumi et al. 2006). Detailed multi-wavelength study of the the recent outburst of RS Oph (Hachisu et al. 2006; Monnier et al. 2006; Sokoloski et al. 2006) and models (Hachisu, Kato, & Luna 2007) suggest a WD of $1.35 \pm 0.01 M_{\odot}$, and that the WD is growing in mass at an average rate of about $1 \times 10^7 M_{\odot} \text{ yr}^{-1}$, which indicates that RS Oph will produce a SN Ia in a few hundred thousand years. Recurrent novae U Sco and CI Aql appear to be similar to RS Oph.

Table 6. RECURRENT NOVAE WITH MASSIVE WHITE DWARFS

	WD mass (M_{\odot})	Period (days)
T CrB	1.37	227.67
RS Oph	1.35	460
V 745 Sco	1.35	...
V3890 Sgr	1.35	...
U Sco	1.37	1.23056
V 394 CrA	1.37	0.7577
IM Nor	...	...
CI Aql	...	...
LMC 1990-2	...	...

13. VY SCULPTORIS NOVA-LIKE SYSTEMS

Long-term monitoring of the transient SSXS RXJ0513.9-6951 (Schaeidt et al. 1993) has revealed quasi-periodic optical intensity dips of about four weeks duration (Reinsch et al. 1996; Southwell et al. 1996), which occur during the X-ray on states. The similarity of the optical behaviour of this SSXS with that of VY Scl stars led Greiner et al. (1999) to suggest that some of the VY Scl stars may indeed be hitherto unrecognized SSXSs. They observed V 751 Cyg with ROSAT HRI and found transient supersoft X-ray emission and anti-correlation of X-ray and optical intensity. The X-ray emission is very luminous and the spectrum is very soft, similar to spectra of SSXSs such as RXJ0513.9-6951.

From the Balmer-line radial-velocity curve of VY Scl, Martinez-Pais et al. (2000) found the orbital period to be 0.232 days. They also found evidence for the presence of a third component. They estimate the mass of the WD to be $1.22 M_{\odot}$ and the secondary star mass to be $0.43 M_{\odot}$. The orbital period of the third star is about 5.8 days. The mass and evolutionary status of the third component is not clear; it may be a normal star of about $0.8 M_{\odot}$ or a low-luminosity higher mass star, in which case it is probably a compact object (Martinez-Pais et al. 2000). The total mass of the 0.232-day orbital period binary is $1.65 M_{\odot}$ WD so it may become a SN Ia.

The detection of supersoft X-ray emission from the VY Scl-type star V 751 Cyg (Greiner et al. 1999) and the detection of a massive WD in VY Scl with 0.232 day orbital period (Martinez-Pais et al. 2000) indicate that some of the VY Scl type systems may become

SNe Ia. Greiner (1998) studied the ROSAT observations of VY Scl stars to investigate the presence, strength and spectrum of soft X-ray emission (0.1 - 2.4 keV). He found soft X-ray emission from 9 out of the 14 VY Scl stars that are detected with ROSAT. Further optical studies of these nova-like stars and determination of their orbital periods and WD masses, and further studies in the X-ray region may enable us to detect some of the systems that may become SNe Ia.

14. SUPER-SOFT X-RAY SOURCES

SSXSs (Table 7) contain accreting WDs (Van den Heuvel et al. 1992). They show soft X-ray spectra with almost all of the flux below 0.5 to 1 keV (Trümper et al. 1991) and luminosities close to the Eddington limit of a $1 M_{\odot}$ star (see the review by Kahabka & Van den Heuvel 1997). Most of the known SSXSs are located in the LMC, SMC, and M31. In the Galactic disk, the high interstellar absorption limits the distance of detectable SSXSs to about 2 kpc. Most of the SSXSs have optical properties reminiscent of low-mass X-ray binaries, which suggests that their optical and UV spectra are strongly affected by soft X-ray irradiation from the accreting WD companion. ROSAT, BEPPOSAX, and ASCA X-ray spectra of most SSXSs indicate that the accreting WDs are very hot.

Table 7. SUPERSOFT X-RAY SOURCES

Object	Period (days)	V(max)	V(min)	L WD (erg s^{-1})
Galaxy				
QR And	0.6605	11.5	12.65	4×10^{36}
MR Vel	4.0288	17.1	17.3	4×10^{35}
LMC				
J0513	0.7628	16.4	17.55	7×10^{37}
J0439	0.1404	...	21.74	9×10^{37}
J0537	0.1458	...	19.66	...
CAL 83	1.0417	16.9	17.5	2×10^{37}
CAL 87	0.4425	...	18.9	5×10^{36}
SMC				
1E0035	0.1719	...	20.3	5×10^{36}

In the model proposed by Van den Heuvel et al. (1992) the relatively massive accreting

WD sustains steady burning of the hydrogen-rich accreted material from a MS or subgiant donor star. They suggested that the accretion has to occur at a finely tuned rate, in the range 1.0 to $4.0 \times 10^{-7} M_{\odot} \text{ y}^{-1}$. At lower rates, hydrogen burning is unstable and occurs in flashes, while at higher rates an extended envelope forms. Rappaport et al. (1994) studied the formation and evolution of such binaries, reproducing their typical luminosities, effective temperatures and orbital periods. They found that there should be more than 1000 SSXSSs in the Galaxy and in M31 and about 100 in the LMC with properties that closely match those of the observed SSXSSs. They found that the orbital periods should be in the range of 0.3 days to 1.4 days, and the WDs should have masses in the range of 0.7 to $1.05 M_{\odot}$ and effective temperatures in the range of 1 to $5 \times 10^5 \text{ K}$. The masses of donor stars are in the range of 1.3 to $2.7 M_{\odot}$. Rappaport et al. (1994) estimated the rate of Galactic SNe Ia resulting from the evolution of SSXSSs to be 0.006 y^{-1} .

Ivanova & Taam (2004) studied the fate of close binary systems (orbital periods 1 to 2 days) that consist of evolved MS donors (1 to $3.5 M_{\odot}$) and WD companions (0.7 to $1.2 M_{\odot}$) and that undergo a phase of mass transfer on a thermal time scale, allowing for the possibility of an optically thick wind driven from the WD. To evolve toward a SN Ia they found that the WD should be relatively massive (more than $0.8 M_{\odot}$) and the donor star needs to be above $2 M_{\odot}$ (but the donor/WD mass-ratio needs to be smaller than three). With these conditions the mass-transfer rates are sufficiently high that surface hydrogen burning provides the bulk of the energy, and the sources are likely to be observed as SSXSSs.

Bitzaraki et al. (2004) performed evolutionary calculations that led to the formation of luminous SSXSSs. They found that the progenitors of the WDs had MS masses $\sim 7 M_{\odot}$ and companions in the range of 1.5 to $3.0 M_{\odot}$. In their calculations they included thermohaline mixing after mass transfer during binary evolution. They concentrated on early case-C evolution which means that the primary fills its Roche lobe when it ascends the early asymptotic giant branch while its core is highly evolved and massive enough to form a CO WD. Their models accounted for the observed properties of SSXSSs such as U Sco and very luminous extragalactic SSXSSs such as CAL 83 in the LMC and the CHANDRA source N1 in M81.

Lanz et al. (2005) did a NLTE model-atmosphere analysis of the LMC SSXS CAL 83 using X-ray spectra obtained with the CHANDRA high-resolution camera and low-energy transmission grating, and XMM-Newton spectra. They found a very rich absorption-line spectrum from the hot WD photosphere but no spectral signature of a wind. They obtained the first direct spectroscopic evidence that the WD is massive ($1.3 M_{\odot}$). They found that low-mass models do not match the observed spectrum as well as high-mass models, and they concluded that $1.0 M_{\odot}$ is a robust lower limit for the WD mass in CAL 83. They found T_{eff}

to be 550,000 K and $\log g = 8.5$. They also found that the short timescale of the X-ray off states (about 50 days; Kahabka 1998) is consistent with a high WD mass. Their analysis of the spectrum of CAL 83 provides direct support for SSXSs as likely progenitors of SNe Ia.

Others also have considered SSXSs as SN Ia progenitors (Branch et al. 1995; Starrfield et al. 2004; Van den Heuvel et al. 1992; Kahabka & van den Heuvel 1997; Hachisu et al. 1999). Hachisu et al. found that the accreting WDs will have strong and hot stellar winds when the mass accretion to the WD exceeds a critical rate. The excess matter transferred above the critical rate is expelled by stellar winds. In such a situation the WD can grow to the CL resulting in a SN Ia. This model, in which a CE does not develop, is called accretion wind evolution. The SSXSs RX J0513.9-6951 and V Sge and a few more SSXSs (Starrfield et al. 2004) are suggested to be examples of SN Ia progenitors via accretion wind evolution. A list of SSXSs and some of their parameters are given in Table 7.

Some symbiotic binaries are SSXSs (e.g., AG Dra; Greiner et al. 1997). A search in the ROSAT archive by Mürst et al. (1996) enabled them to sort the symbiotic stars into three types based on the hardness of their X-ray spectra. Symbiotic binaries Ln 358, Dra C-1, R Aqr, AG Dra, RR Tel (a symbiotic nova), and CD -43 14304 were found to show SSXS characteristics. There are a few symbiotic binaries with harder X-ray spectra, which may be due to colliding hot winds. Some of the symbiotic binaries with the hardest X-ray spectra may contain massive accreting WDs or accreting neutron stars.

Some classical and recurrent novae have been detected as luminous SSXSs during the late-decline phase of their outbursts (e.g., V 1974 Cyg = Nova Cyg 1992, Balman et al. 1998; GQ Mus = Nova Mus 1983, Shanley et al. 1995; and U Sco, Kahabka et al. 1999).

The recurrent nova U Scorpii is found to be a SSXS with a hot and massive accreting WD (Kahabka et al. 1999). The WD T_{eff} is estimated to be 9×10^5 K. The donor is a MS star of $1.5 M_{\odot}$. The system is an eclipsing binary with an orbital period of 1.23 days (Schaefer & Ringwald 1995; Thoroughgood et al. 2001). The mass of the WD is $1.37 M_{\odot}$ (Bitzaraki et al. 2004; Thoroughgood et al. 2001), very close to the CL. U Sco shows nova outbursts almost every eight years. It has shortest known recurrence period (Iijima 2002). The outburst mechanism for the U Sco subclass of recurrent novae is similar to the thermonuclear runaway model of classical nova outbursts (Starrfield, Sparks & Truran 1985). The helium abundance in the ejecta of U Sco (Iijima 2002) is similar to that found in the ejecta of normal classical novae. Some authors have estimated higher helium abundance in the ejecta of U Sco (Barlow et al. 1981). It is important to derive an accurate helium abundance from analysis of high-resolution spectra in order to find out if the donor star is a normal star or a helium-rich star. Thoroughgood et al. (2001) proposed that U Sco is the best SN Ia progenitor currently known and estimated that it will be a SN Ia in $\sim 7 \times 10^5$

years. From evolutionary calculations Bitzaraki et al. (2004) also consider U Sco to be a good SN Ia candidate.

15. V SAGITTAE-TYPE CLOSE BINARIES

Most of the known SSXSs are located in external galaxies (Greiner 1996), which makes detailed optical observations difficult. It is therefore of great interest to identify galactic SSXSs and related stars. X-ray surveys have not been able to detect many Galactic SSXSs because the soft X-ray emission is strongly attenuated by the interstellar medium. It has been suggested that V Sge-type close binary stars (V Sge, V617 Sgr, HD 104994, WX Cen, and T Pyxidis; see Table 8) have spectroscopic and photometric properties that are very similar to those of SSXSs (Steiner & Diaz 1998; Patterson et al. 1998; Greiner & van Teeseling 1998; Simon 2003). This suggestion is based on characteristics which are typical for SSXSs, but are rare or even absent among canonical CVs: (1) the presence of both O VI and N V emission lines, (2) a He II (4686Å) to H β emission-line ratio greater than 2, (3) high luminosities and very blue colors, and (4) orbital light curves that are characterized by wide, deep eclipses similar to those observed in some of the SSXSs (Hachisu 2004).

V Sge is a very blue star that varies in brightness from 9.6 to 14.7 magnitudes with a mean around 11.6. It is an eclipsing and double-lined spectroscopic binary with a period of 0.5142 days. The WD mass is estimated to be 1.0 to 1.3 M_{\odot} and the mass of the companion is estimated to be 2 to 3 M_{\odot} . The complex nature of the variable light curve and spectrum makes it difficult to derive accurate parameters. The optical spectrum shows complex emission lines (Patterson et al. 1998; Steiner & Diaz 1998). Greiner & van Teeseling (1998) studied the X-ray properties of V Sge and its relation to the SSXSs. They found that

Table 8. V Sge-CLOSE BINARIES

	Period (hours)	V	(B-V)	(U-B)	W-R type
V Sge	12.34	11.6	0.0	-0.9	WN5
V617 Sgr	4.97	14.8	-0.04	-0.87	WN5
HD 104994	7.46	10.9	0.06	-0.84	WN3(pec)
WX Cen	10.0	13.7	0.4	-0.7	WN7
HD 45166	0.357	9.88	...	...	...
T Pyxidis	1.92	...	...	...	...

during optically bright states, V Sge is a faint, hard X-ray source, while during optically faint states (V magnitude fainter than 12), it has properties similar to those of SSXSs. They explain the different optical and X-ray states by a variable amount of extended uneclipsed matter, which during the optically bright states contributes significantly to the optical flux and completely absorbs the soft X-ray component. An additional, perhaps permanent, hard X-ray component seems to be present in order to explain the X-ray properties during the optically bright, hard X-ray state. The anti-correlation of soft X-ray emission with optical brightness of V Sge is similar to that observed in RXJ0513.9-6951, a transient SSXS in the LMC (Reinsch et al. 1996; Southwell et al. 1996). RXJ0513.9-6951 turns on as a SSXS only during 1 magnitude optical dips, which occur every 100 to 200 days and last about 30 days. This behaviour has been explained by assuming expansion and contraction of the shell-burning WD. The model that has been suggested for RXJ0513.9-6951 cannot explain the observed X-ray data of V Sge: the optical brightness changes of V Sge are very rapid — both the faint-bright-state transitions as well as the succession of different faint states may occur on timescales of less than 1 day.

Hachisu (2004) proposed a model to explain the long-term light-curve variations of the SSXSs V Sge and RXJ0513.9-6951 based on an optically thick wind model of mass-accreting WDs. The observed long-term light curves of V Sge and RXJ0513.9-6951 are very similar (Hachisu 2004). When the mass accretion rate exceeds the critical rate of $1 \times 10^{-6} M_{\odot} \text{ y}^{-1}$, optically thick strong winds begin to blow from the WD, and the WD can accrete and burn hydrogen-rich matter on the surface at the critical rate. The excess matter is expelled in the wind and the WD can grow to the CL resulting in a SN Ia. Using the accretion wind evolution model they were able to reproduce the transition between the optically high (X-ray-off) state and the optically low (X-ray-on) states of RXJ0513.9-6951 and V Sge.

WX Cen = WR 48c is a V Sge type close binary with an orbital period of 0.417 days. The light curve and spectrum of WX Cen are similar to those of V Sge. Based on the accretion rate ($10^{-7} M_{\odot} \text{ y}^{-1}$), the WD mass ($1.16 M_{\odot}$) and the short orbital period Oliveira & Steiner (2004) estimated that in $\sim 5 \times 10^6$ years WX Cen may become a SN Ia..

Two other V Sge-type close binaries are V 617 Sgr and HD104994 = DI Cru. V 617 Sgr is a close binary with an orbital period of 4.97 hours. The light curve and spectrum of V 617 Sgr are very similar to V Sge. X-ray emission has been detected from HD 104994. The orbital period is 6.78 hours. The light curve, its asymmetries, and the flickering of HD 104994 are similar to those of V Sge and V 617 Sgr. Steiner et al. (2006) find that the orbital period of V 617 Sgr to evolve quite rapidly which is consistent with the idea that V 617 Sgr is a wind driven accretion supersoft source. They consider that it is similar to the wind driven supersoft X-ray binaries SMC 13 and T Pyx. They consider that V 617 Sgr will

evolve into a Type Ia supernova in few million years. All the above mentioned V Sge-type systems have close similarities to SSXs. Patterson et al. (1998) considered T Pyxidis to be similar to V Sge-type stars and SSXs. T Pyx has a high-excitation spectrum, very blue colors, and very high luminosity similar to that of V Sge (Patterson et al. 1998).

Further multiwavelength long-term spectroscopic and photometric monitoring of these systems is needed to derive accurate masses of the WDs and donor stars, and accretion and mass-loss rates. Also, from an analysis of SDSS spectra we may be able to detect new V Sge-type systems with optical spectra similar to those of V Sge and SSXs. A few hundred V Sge-type systems are expected to exist in the Galaxy. Since the optical spectra show O VI, N V, and He II it may be possible to detect new V Sge-type systems in SDSS data using the V Sge spectrum as a template.

16. BINARITY OF WHITE DWARFS WITH HARD X-RAY EMISSION

WDs themselves do not emit hard (greater than 0.5 keV) X-rays but if a WD accretes material the released gravitational energy may power hard X-ray emission. The most likely source to provide material for accretion onto a WD is a binary companion. Alternatively, if a WD has a binary companion with strong coronal activity, the hard X-ray emission may come from the companion. Either way, hard X-ray emission from WDs implies the presence of binarity. Fleming et al. (1996) found nine DA WDs with hard X-ray emission using the ROSAT all-sky survey, and all nine have late-type (F to M) companions. O'Dwyer et al. (2003) made a systematic search for hard X-ray emission from WDs by correlating the WD catalog of McCook & Sion (1999) and the ROSAT point-source catalog of White et al. (2000). They found 76 WDs coincident with X-ray sources at a high level of confidence. (Multiwavelength studies and radial-velocity monitoring, and near-IR photometry of WDs with hard X-ray emission may reveal late-type companions). Among these sources, 17 show significant hard X-ray emission at energies greater than 0.5 keV, and 12 are in known binaries; in two of these the accretion of the close companion's material onto the WD produces the hard X-rays, and in the other 10 the late-type companion's coronal activity plus accretion of material from coronal ejections and stellar winds seem to cause the hard X-rays. Some of the WDs with hard X-ray emission are found to be the hottest in the sample. Chu et al. (2004) used an updated list of WDs and the final ROSAT point-source catalog to find 47 new X-ray sources convincingly coincident with WDs. Five of these have hard X-ray emission and late-type companions. From further multiwavelength studies of WDs with hard X-ray emission we may be able to find some accreting systems with F, G, and K companions.

17. DOUBLE DEGENERATES

Several systematic searches for double WD (DD) binaries have been made (Napiwotzki et al. 2004). The radial-velocity surveys have found about 120 DDs. They found only one massive DD system, with total mass ($1.24 M_{\odot}$), still about 10 percent below the CL. Also the long orbital period of 12.5 hours shows that it is not a good candidate for SN Ia within a Hubble time. None of the systems qualify as SN Ia progenitors because the total mass is much smaller than the CL. In fact, most of the individual masses seem to be smaller than $0.45 M_{\odot}$, the approximate core-mass limit for helium ignition, therefore they are helium WDs.

The only likely SN Ia progenitor in this sample is not a DD, but the sdB + WD binary KPD 1930+2752 (Maxted et al. 2000). The orbital period is 2.283 hours, the mass of the sdB star is $0.55 M_{\odot}$, and the mass of the WD is $0.97 M_{\odot}$. The system may merge in less than 0.2 Gyr, perhaps resulting in a SN Ia. Geier et al. (2006) analyzed time resolved spectroscopy of KPD 1930+2752 and found that the total mass exceeds the CL. The total mass and the merging time of the binary indicate that it is a very good candidate for a SN Ia progenitor (Geier et al. 2006).

18. EVOLUTIONARY MODELS

Langer et al. (2000) studied the evolution of CO WD and MS (single degenerate; SD) systems that may become SNe Ia. They found that WDs with initial mass as small as $0.7 M_{\odot}$ can produce SNe Ia. They found an upper limit for donor stars of $2.3 M_{\odot}$. Langer et al. (2000) limited the maximum possible wind mass-loss rate to three times the Eddington limit of the accreting WDs. They considered only case A mass transfer.

Recently Han & Podsiadlowski (2004) also carried out a detailed study of evolutionary models of CO WD and MS systems, using Eggleton’s stellar evolution code. They performed binary stellar evolution calculations for about 2300 close WD binaries and mapped the initial parameters in the orbital period - secondary mass plane, that may become SNe Ia. They confirm the result of Langer et al. that WDs with mass as low as $0.67 M_{\odot}$ can accrete efficiently and reach the CL. They did not limit the mass-loss rate and they considered both case A and case B mass transfer. Their upper limit for donor stars was $3.7 M_{\odot}$.

Belczynski et al. (2005) used the StarTrack population synthesis code to discuss potential progenitors of SNe Ia. They found that the SD scenario can explain the observed delay times for models with low common-envelope efficiency. Höflich et al. (1996) and Nugent et al. (1997) found that the observed properties of SNe Ia favor WDs at the CL, while the

sub-CL mass models do not explain even subluminoous, red SN Ia.

Fedorova, Tutukov & Yungelson (2004) considered scenarios for the evolution of close binaries resulting in the formation of semi-detached systems in which a WD can reach the CL by accretion from a MS or SG companion of mass $2 M_{\odot}$. From population synthesis studies of these systems, they found that the model occurrence rate of SNe Ia in semi-detached systems is $0.2 \times 10^{-3} \text{ y}^{-1}$, less than 10 percent of the observational estimate of the Galactic occurrence rate of SNe Ia. Thus, in their model, this channel for formation of progenitors of potential SN Ia is not able to produce more than 10 percent of all SNe Ia in our Galaxy.

Greggio (2005) presented formalism to relate the rate of SNe Ia in stellar systems to their star-formation history through two fundamental characteristics of the SN Ia progenitor model : the realization probability of the SN Ia scenario from a single-age stellar population, and the distribution function of the delay times, which is proportional to the SN Ia rate after an instantaneous burst of star formation. Greggio (2005) suggests that different channels (SD CL, sub-CL, and DD CL) could contribute to SNe Ia, each with its own probability, as in the realizations of the population synthesis models. Some of the differences in the observed properties of SNe Ia seem to support the above mentioned notion (Benetti et al. 2005). The different luminosities at maximum, the different light-curve decline rates, and the differences in parent galaxies may be due to different typical progenitors. If both SD and DD channels are at work, Greggio’s (2005) study indicates that in early-type galaxies the DD channel should prevail over SD events and in late-type galaxies a large proportion of SNe Ia may be from SD systems.

19. CONCLUSION

Based on the above mentioned variety of single degenerate close binary systems further mutli-wavelength long term monitoring and modeling of the following promising SD candidates — HR 8210 (=IK Peg), HD 209295, V 471 Tau, U Sco, RS Oph, V394 CrA, CAL 83, QR And, RXJ0513.9-6951, V Sagittae-type close binaries V Sge, V617 Sgr, T Pyxidis and KPD 1930+2752 — needs to be carried out. These systems deserve high priority in observations and modeling in order to better determine the masses and orbital parameters, to further understand the accretion onto the white dwarfs, and to predict whether the systems will become SNe Ia.

Because there are so many promising single-degenerate candidate systems, and no known promising double-degenerates, we suspect that SDs are responsible for some or perhaps all SNe Ia, while DDs are responsible for some or perhaps none.

This work has been supported by NSF grants AST-0204771 and AST-0506028, and NASA LTSA grant NNG04GD36G.

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